**Introduction**

Schottky diodes are used in a variety of ways to implement multisource power systems. For instance, high availability electronic systems, such as network and storage servers, use power Schottky diode-OR circuits to realize a redundant power system. Diode-ORing is also used in systems that have alternate power sources, such as an AC wall adapter and a backup battery feed. Power diodes can be combined with capacitors to hold up a load voltage during an input brownout. In this case, the power diodes are placed in series with the input voltage, with the capacitors on the load side of the diode. While the capacitors provide power, the reverse-biased diode isolates the load from the sagging input.

Schottky diodes suffice for these applications when currents are below a few amperes, but for higher currents, the excess power dissipated in the diode due to its forward voltage drop demands a better solution. For instance, 5A flowing through a diode with a 0.5V drop wastes 2.5W within the diode. This heat must be dissipated with dedicated copper area on the PCB or heat sinks bolted to the diode, both of which take significant space. The diode’s forward drop also makes it impractical for low voltage applications. This problem calls out for an ideal diode with a zero forward voltage drop to save power and space.

The LTC4352 ideal diode controller in tandem with an N-channel MOSFET creates a near-ideal diode for use with 0V to 18V input supplies. Figure 1 illustrates the simplicity of this solution. This ideal diode circuit can replace a power Schottky diode to create a highly efficient power ORing or supply holdup application. Figure 2 shows the power savings of the ideal diode circuit over a Schottky diode. 3.5W is saved at 10A, and the saving increases with load current. With its fast dynamic response, the controller excels in low voltage diode-OR applications which are more sensitive to voltage droop.
What Makes It Ideal?

The LTC4352 monitors the differential voltage across the MOSFET source (the “anode”) and drain (the “cathode”) terminals. The MOSFET has an intrinsic source-to-drain body diode which conducts the load current at initial power-up. When the input voltage is higher than the output, the MOSFET is turned on, resulting in a forward voltage drop of $I_{LOAD} \cdot R_{DS(ON)}$. The $R_{DS(ON)}$ can be suitably chosen to provide an easy 10x reduction over a Schottky diode’s voltage drop. When the input drops below the output, the MOSFET is turned off, thus emulating the behavior of a reverse biased diode.

An inferior ideal diode control technique monitors the voltage across the MOSFET with a hysteretic comparator. For example, the MOSFET could be turned on whenever the input to output voltage exceeds 25mV. However, choosing the lower turn-off threshold can be tricky. Setting it to a positive forward voltage drop, say 5mV, causes the MOSFET to be turned off and on repeatedly at light load currents. Setting it to a negative value, such as -5mV, allows DC reverse current.

The LTC4352 implements a linear control method to avoid the problems of the comparator-based technique. It servos the gate of the MOSFET to maintain the forward voltage drop across the MOSFET at 25mV (AMP of Figure 3). At light load currents, the gate of the MOSFET is slightly above its threshold voltage to create a resistance of $25mV/I_{LOAD}$. As the load current increases, the gate voltage rises to reduce the MOSFET resistance. Ultimately, at large load currents, the MOSFET gate is driven fully on, and the forward voltage drop rises linearly with load current as $I_{LOAD} \cdot R_{DS(ON)}$. Figure 4 shows the resulting ideal diode I-V characteristic.

In a reverse voltage condition, the gate is servoed low to completely turn off the MOSFET, thus avoiding DC reverse current. The linear method also provides a smooth switchover of currents for slowly crossing input supplies in diode-OR applications. In fact, depending on MOSFET and trace impedances, the input supplies share the load current when their voltages are nearly equal.

Fast Switch Control

Most ideal diode circuits suffer slower transient response compared to conventional diodes. The LTC4352, on the other hand, responds quickly to changes in the input to output voltage. A powerful driver turns off the MOSFET to protect the input supply and board traces from large reverse currents. Similarly, the driver turns on the switch rapidly to limit voltage droop during supply switchover in diode-OR applications.

Figure 5 shows a fast switchover event occurring in a 3.3V ideal diode-
Design Features

OR circuit. Initially $V_{IN1}$ supplies the entire load current since it is higher than $V_{IN2}$. In this state, MOSFET Q1 is on and Q3 is off. A short circuit causes $V_{IN1}$ to collapse below $V_{IN2}$. The LTC4352’s fast response shuts off Q1 and turns on Q3 so that the load current can now be supplied by $V_{IN2}$. This fast switchover minimizes disturbance on the load voltage so that downstream circuits can continue to operate smoothly.

To achieve fast switch turn-on, the LTC4352 uses an internal charge pump with an external reservoir capacitor. This capacitor is connected between the CPO and SOURCE pins. CPO is the output of a charge pump that can deliver up to 100µA of pull-up current. The reservoir capacitor accumulates and stores charge, which can be called upon to produce 1.5A of transient GATE pull-up current during a fast turn-on event. The reservoir capacitor voltage drops after the fast turn-on since it charge-shares with the input gate capacitance ($C_{iss}$) of the MOSFET. For an acceptable drop, the reservoir capacitor value should be around 10 times the $C_{iss}$ of the MOSFET.

It is easy to disable fast turn-on. Omitting the reservoir capacitor slows down the gate rise time as determined by the CPO pull-up current charging $C_{iss}$. Slow gate turn-on may cause the load to drop roughly a volt below the input as current flows through the MOSFET body diode until the channel is enhanced. This may be acceptable at higher input voltage applications, such as 12V.

### Do What No Diode Has Done Before

The LTC4352 goes above and beyond the functionality of a diode by incorporating input undervoltage and overvoltage protection, outputs to report status and fault information, open MOSFET detection, and the ability to allow reverse current.

Figure 6 shows the LTC4352 in a 5V ideal diode circuit with undervoltage and overvoltage protection. The UV and OV pins have comparators with a 0.5V trip threshold and 5mV hysteresis (Figure 3). The resistive dividers from the input supply to these pins set up an input voltage window, typically 4.36V to 5.78V, where the ideal diode function operates. The STATUS pin pulls low to light up a green LED whenever the gate is high and power is flowing through the external MOSFET. For $V_{IN}$ outside the input voltage window, the gate is held off and the FAULT pin pulls low to signal a fault condition. A red LED, D2, provides visual indication.

The MOSFET switch could fail open circuit or its $R_{DS(on)}$ may degrade over years of operation, increasing the voltage drop across the switch. A large drop also results when excessive current flows through the MOSFET, possibly due to an output short circuit. The LTC4352 detects such failures and flags it through its FAULT pin. The open MOSFET detection circuit trips whenever it senses more than 250mV of forward voltage drop across the MOSFET—even with the gate turned off. Note that this condition only causes the FAULT pin to pull low, but no action is taken to turn off the switch. Table 1 translates STATUS and FAULT LED status to the operating state of the LTC4352.

The input at the REV pin configures the LTC4352’s behavior for reverse current. It is tied low for normal diode operation, which blocks reverse current from flowing through the external MOSFET. Driving REV above 1V turns the gate completely on to its limit, even during reverse current conditions.

### Table 1. Operating state of the LTC4352 ideal diode as indicated by the STATUS and FAULT lights

<table>
<thead>
<tr>
<th>LED State</th>
<th>Ideal Diode Operating State</th>
</tr>
</thead>
<tbody>
<tr>
<td>STATUS</td>
<td>MOSFET</td>
</tr>
<tr>
<td>Green LED</td>
<td>OFF</td>
</tr>
<tr>
<td>Red LED</td>
<td>ON</td>
</tr>
<tr>
<td>OPEN</td>
<td>OFF</td>
</tr>
</tbody>
</table>

![Figure 6. A 5V ideal diode circuit with input undervoltage and overvoltage protection. Ideal diode function operates for 4.36V < $V_{IN}$ < 5.78V, else GATE is low.](image-url)
DESIGN FEATURES

Only undervoltage, overvoltage, and VCC undervoltage lockout can override this to turn-off the gate. This feature is handy either in power path control applications which allow reverse current flow to occur, or for testing purposes.

**Inrush Control on a Hot Swap Board**

When the diode power input flows across a connector on a hot swap board, the LTC4352 can do double-duty to control the inrush current. Again, back-to-back MOSFETs are required for this application to block conduction through the MOSFET body diodes. The inrush current is limited by slowing the rate of the load voltage. This is done by limiting dV/dt on the MOSFET gate and operating it in a source-follower configuration.

Figure 7 illustrates an application where the LTC4352 is used for inrush control. Since the goal is to limit dV/dt on the gate, the fast turn-on characteristic of the ideal diode is disabled by omitting the CPO reservoir capacitor. The gate current is now limited to the CPO pull-up current of 100µA. To further reduce dV/dt, an RC network is added on the gate. The resistor decouples the capacitor during fast turn-off due to reverse current or overvoltage faults.

Resistor R_G prevents high frequency oscillations in Q2. When the board is hot-plugged, the long power pins make contact first. The LTC4352 powers up, but holds the gate off since UV is low. After a few milliseconds of board insertion delay, the short UV pin makes contact. If V_IN is above 10.8V, the MOSFET gate starts ramping up. The MOSFET turns on as the gate reaches the threshold voltage, and current starts charging the output. Q2 operates in the source follower mode and suffers the most power dissipation. Its V_DS starts off at V_IN and decreases to 25mV/2. Care should be taken that the power dissipated during inrush falls within the safe operating area (SOA) of the MOSFET.

**Down to Earth Operation**

The V_IN operating range extends all the way down to 0V. However, when operating with inputs below 2.9V, an external supply is needed on the VCC pin. This supply should be in the range 2.9V to 6V. For a 2.9V to 4.7V subset of this range, V_IN should always be lower than V_CC. A 0.1µF bypass capacitor is also needed between the V_CC and GND pins. Figure 8 shows an ideal diode circuit, where a 5V supply powers up the V_CC pin. In this case, V_IN can operate all the way down to 0V and up to 18V.

For input supplies from 2.9V to 18V, the external supply at the V_CC pin is not needed. Instead, an internal low dropout regulator (LDO in Figure 3) continued on page 31

Figure 8. A 0V to 18V ideal diode circuit. By powering the V_CC pin with an external supply in the 4.7V to 6V range (here 5V), V_IN can operate down to 0V and up to 18V.
and tighter power budgets. Another computation in smaller form factors system design has been to pack more an ever-present theme in electronic bypassing and LDO stability.

0.1µF V approximately 50mV below V pin. For V

LTM4608, continued from page 27
demonstrates the small temperature for a more reliable system. Figure 7 LTM4604, LTM4608, continued from page 29

than 5% at full load. Excellent current sharing results in well balanced thermal stresses on the paralleled LTM4608s, which in turn makes for a more reliable system. Figure 7 demonstrates the small temperature difference between these two paral-

LTC4352, continued from page 27 generates a 4.1V supply at the VCC pin. For VIn below 4.1V, VCC follows approximately 50mV below VIn. The 0.1µF VCC capacitor is still needed for bypassing and LDO stability.

Conclusion
An ever-present theme in electronic system design has been to pack more computation in smaller form factors and tighter power budgets. Another trend has been to lower the voltage of distributed power, which increases the current to maintain power levels. Given these constraints, board designers must scrutinize each diode in a high current power path for its power and area consumption.

The LTC4352 MOSFET controller provides the same functionality as a diode but at higher efficiencies and cooler temperatures, especially as currents increase. It also incorporates useful features such as fast switch control, 0V operation, undervoltage and overvoltage protection, open MOSFET detection, ability to allow reverse current, Hot Swap capability, and fault and status outputs. All of this functionality comes wrapped in space-saving 12-pin DFN (3mm x 3mm) and MSOP packages, making it possible to produce an ideal diode solution in a smaller footprint than conventional diodes.

Conclusion
The LTC3513 is a comprehensive, but compact, power supply solution for TFT-LCD panels. Its wide input range and low power dissipation allow it to be used in a wide variety of applications. All four of the integrated switching regulators have a 2MHz switching frequency and allow the exclusive use of the ceramic capacitors to minimize circuit size, cost and output ripple.